Dynamics models of soil organic carbon

YANG Li-xia, PAN Jian-jun

College of Resource and Environment of Nanjing Agricultural University, Nanjing 210095, P. R. China

Abstract: As the largest pool of terrestrial organic carbon, soils interact strongly with atmosphere composition, climate, and land change. Soil organic carbon dynamics in ecosystem plays a great role in global carbon cycle and global change. With development of mathematical models that simulate changes in soil organic carbon, there have been considerable advances in understanding soil organic carbon dynamics. This paper mainly reviewed the composition of soil organic matter and its influenced factors, and recommended some soil organic matter models worldwide. Based on the analyses of the developed results at home and abroad, it is suggested that future soil organic matter models should be developed toward based-process models, and not always empirical ones. The models are able to reveal their interaction between soil carbon systems, climate and land cover by technique and methods of GIS (Geographical Information System) and RS (Remote Sensing). These models should be developed at a global scale, in dynamically describing the spatial and temporal changes of soil organic matter cycle. Meanwhile, the further researches on models should be strengthen for providing theory basis and foundation in making policy of green house gas emission in China.

Keywords: Soil carbon; Soil organic carbon; Dynamic model

CLC number: S159.2 **Document code:** A **Article ID:** 1007-662X(2003)04-0323-08

Introduction

Soil organic carbon plays a very important role in global carbon cycle and global change, as it is the largest terrestrial Carbon-pool. Although soil organic carbon is the largest terrestrial carbon reservoir, its mass is the least certainly (Bolin *et al.* 1979). The storage of organic carbon in soils on a global scale was estimated to be between 700-Pg and 3 000-Pg carbon (Bouwman 1990), thereof, the total global soil organic carbon accounts to about 1500-Pg carbon in top of 1-m soil layer (Adams *et al.* 1990; Eswaram *et al.* 1993), and are double of the amount of 750-Pg carbon in atmosphere as CO_2. Lai (1999) gave a conservative estimate of soil carbon pool as 2300-Pg carbon, which is about fourfold of biotic pool, and about three times of the atmospheric carbon pool. It has recently been suggested that soil carbon may play an important role as source or sink of carbon in response to changing climate and atmosphere CO_2.

Many researches show that the part of missing carbon sink may reside in terrestrial ecosystem. However, some factors affect soil organic carbon dynamics, for example, soil texture, soil temperature, land use and vegetation. Cultivation has caused reductions in carbon contents of agricultural soils and increases in atmospheric CO_2 concentrations. Soil organic carbon loss increases with the increasing of soil temperature. However, soil clay content increases soil stability, but their interrelations are not very clear. At present, the effect of global warming will be to accelerate the decomposition of soil organic carbon. Thereby releasing CO_2 to the atmosphere will further enhance the warming trend (Jenkinson 1991). So the effects of soil organic carbon dynamics on atmospheric carbon dioxide concentration in the light of global climate change are now in the forefront of ecological research. Our capacity to predict and ameliorate the consequences of climate change depends, in part, on a clear understanding of soil organic carbon and its dynamic change. The dynamic changes of soil organic carbon have a strong effect on atmospheric composition and the rate of climate changes. As their complicated interactions are hard described by experiments, some models are utilized to provide an effective way to explore. These models can be regarded as theory basis and foundation for making policy of green house gas emission in China. As is known, in the future, soil organic carbon models will be used to assess the impact of global change on soil organic matter and subsequent feedback effects.

Related models worldwide

Various models have been developed to simulate the carbon dynamics in soil. Most of the models can describe the turnover rate of soil organic carbon as a sum of multiple and parallel compartment, and each compartment has its own turnover rate. Those compartmental models are conceptually simple and popular, but the compartment models require the size and turnover rate for each compartment,

Foundation item: The research is funded by National Natural Science Foundation (40231016) and Canadian International Development Agency (CIDA).
Biography: YANG Li-xia (1976-), female, Postgraduate in Nanjing Agricultural University, Nanjing 210095, P. R. China.
E-mail: yanglixianj2001@163.com.
Received date: 2003-06-23
Responsible editor: Zhu Hong

which is difficult to obtain from field studies. With the development of models, some models were used to calculate the size and turnover rate for each compartment by remote sensing data (net primary production). Nonetheless, those models have provided us a way to evaluate the potential role of temperature, moisture and soil texture on the turnover rate of organic carbon in soils.

Models in China

In the1980s, the models were only stable but not dynamic ones in China. The models were only simplified statistical ones, which were not considered in the interrelations of global change, land use and vegetation, distribution of spatial and temporal change of soil. These models can only explain the states of sites measured. At present, some dynamics models have been developed.

Two-composition model

Li Zhongpei and Wang Xiaoju (1998) adopted Two-composition model to simulate soil organic carbon content by using some investigated and measured datasets. The model was used to divide the soil organic carbon into new inputted and native soil organic carbon. Each formation is transformed by first-order dynamics equation. The model can simulate dynamics process of soil organic carbon change at the beginning of land use change in different soil types, however, it is a statistical model according to empirical interrelation. In the model, the effects of temperature and water feedback in dynamics process on soil organic carbon were not considered.

SCNC model

Wu Jinshui (2003) studied and developed a computerized simulated model on soil organic matter and nutrient cycle. The model contains equilibrium and predicted model. The equilibrium model shows that each of compartment content of soil organic carbon is measured when organic carbon is inputted to simulate soil organic carbon to reach equilibration. Predicted ones actually simulate soil carbon dynamics on the basis of equilibrium. SCNC model can be divided into six parts and each is discomposed in proportion by dynamics first-order equation. In the model, climatic condition, soil texture, cropping and vegetation are considered. Climatic condition, especially temperature and humidity change, can change soil biomass and soil property, which further affects soil organic matter decomposition. Vegetation also has an influence on soil water. These factors are corrected by coefficients. SCNC model is a month-step one and is used to calculate soil organic carbon content by matrix transformation. The model is only developed on base of hypothesis that input organic matter decomposition is restricted by certain proportional, but which is not appropriate to soil complicated matter.

In addition to these models, there are some other models established in agro-ecosystems. Huang *et al.* (2001) developed a computer model to simulate soil organic matter dynamics (Fig. 1). Organic matter in soils was divided into two parts including additional organic carbon, which was inputted from crop residues or other sources and soil intrinsic carbon. The additional organic carbon was assumed that it consists of two components, readily decomposable and inert soil organic carbon. The model was represented by a differential equation. And an integral equation was affected by environmental conditions including soil temperature, soil water status and soil texture. In the experiment, five different temperatures were assumed. From derived non-linear analysis, their interrelations between temperature and incubation time were gained. Another two functions were adopted in the same method. From the three conception functions and assumed assumption, a soil organic matter model is derived. At present, soil organic carbon models are mostly based on stable models because the related researches have been developed late and datasets accumulated are not well progressed in China. Most models simplify soil organic matter processes and adopt mathematic analysis to simulate soil organic matter dynamics, which can not explain terrestrial carbon cycling on complicated interrelations with climatic change, vegetation cover and soil. In a word, soil organic carbon model in China is being developed toward large-scale, which can describe spatial and temporal distribution. The model mechanistic and its feedback on climatic change will be improved.

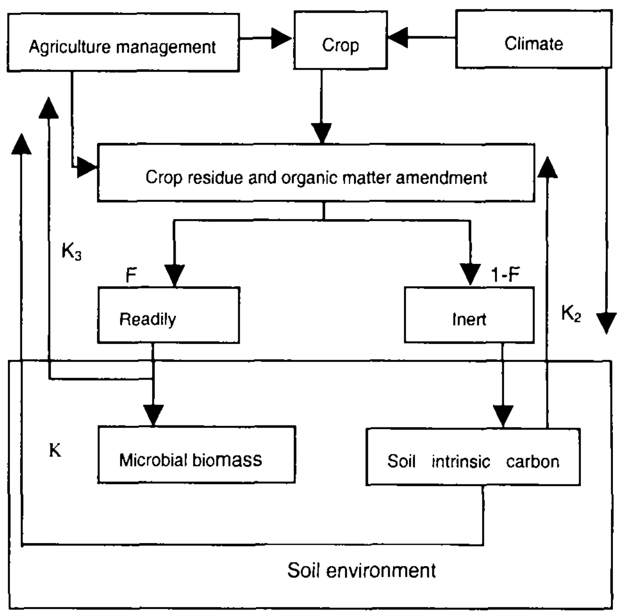

Fig. 1 Conceptual explanation for dynamics model of soil carbon

Models in other countries

The models are process-oriented and multi-compartment models. They were mainly empirical in nature and all contained a slow or inert pool of organic carbon according to turnover rates. Soil temperature and soil moisture are the driving variables of the models. Soil texture is used in some

models to modify decomposition progress. About half the models treat the soil as homogeneous layer with no consideration to depth.

Rothamsted soil-carbon turnover model

The model is a mechanistic one-discrete to continuous form (Jenkinson 1977; Jenkinson 1990). It is assumed that there are 5 major compartments, and that transfer of carbon from compartment to compartment by decomposition processes is by a first-order process.

These fractions consist of decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified organic matter (HUM) and inert organic matter (IOM). The model assumes that each fraction containsa single species which undergoes biological decomposition by the first-order process (Jenkinson *et al.* 1977; Jenkinson 1990). In the model, the organic carbon inputs are assumed to enter the DPM and RPM pool, which decomposes to form CO_2, microbial biomass and humified organic matter. For handling the model with the limited data available, it was necessary to make the further simplification, so the biomass stabilized microbial metabolites, and CO_2 are all formed in the same proportion. When substrate carbon is metabolized by the biomass, a fraction α is incorporated into the microbial biomass compartment, a fraction β enters the humus compartment, and the rest is liberated as CO_2. However the formulation of this model differs from that of other major soil-carbon models. In the model, the decomposition rate of organic matter of each compartment conforms to exponential decay The model shows that the sums-of exponentials model may be converted to a continuous form, which will be an asymptotic approximation of a first-order differential equation system, where the rate constants in the sums-of-exponentials model approximate ones in a first-order linear differential equation form. It is largely used in climate-change and land-use studies (Jenkinson *et al.* 1991).

Base on the Rothamsted long-term agricultural experimental data and radiocarbon (^{14}C) dating of the archived soil samples, Jenkinson and Rayner (1977) calibrated their soil organic carbon turnover model and estimated the sizes and turnover times of the five soil organic carbon compartments. The dataset is probably the most complete one in the world for calibrating of a multi-compartmental soil organic carbon model.

CENTURY model

CENTURY model (Parton *et al.*1987, 1993; Metherell *et al.* 1993) is a semi-mechanistic process-based model of terrestrial biogeochemistry, based on relationships between climate, human management (fire, razing), soil properties, plant productivity, and decomposition. A soil organic matter sub-model that includes dynamic C and N flows in soil and litter pools are contained. The submodel consists of eight organic matter pools, and the four pools represent soil organic matter (Fig. 2). The soil organic matter pools include two 'active' fractions that have rapid turnover times (0.5-1 years) representing microbial biomass and metabolites divided into a surface and a soil pool; a 'slow' fraction with intermediate turnover time (10-50 years) that represents stabilized decomposition products; and a 'passive' fraction with slow turnover time (1000-5000 years) that represents highly stabilized organic matter. Carbon flows between these pools are controlled by decomposition rate and microbial respiration parameters, both of which are expressed as functions of soil texture. The model was used, in a monthly time, to simulate the dynamics of soil organic matter over long time period (100 to 10000 years) and the impact of cultivation (100 years) on soil organic matter dynamics, nutrient mineralization, and plant production. It more successfully simulates the dynamics of grasslands, forests, crops, and savannas. But the soil depth considered in Century model is only in the depth of 20-cm soil layer. The dynamics of soil C for deeper soil layer (20-50 cm) which may be substantial (Parton *et al.* 1994) are not considered in the model.

The DAISY model

DAISY is a semi-mechanistic process-model that stimulates crop production, soil water and C and N dynamics in agro-ecosystems. The Soil Organic Matter sub-model (Fig. 4) of the soil-plant-atmosphere model DAISY simulates three organic pools with organic matter (AOM), soil microbial biomass (SMB) and native nonliving soil organic matter (SOM), mineral N and soil respiration (CO_2). Each organic pool is considered to be a continuum with a certain range of turnover rates. It is assumed that the turnover rate of the pools follows first order kinetics. Hence, the turnover rate of each sub-pool is described by the following equation:

$$\frac{dX}{dt} = k_x C_x \tag{1}$$

where, $\frac{dx}{dt}$ is the turnover rate of pool X (kg·m^{-3}·d^{-1}), k_x is the coefficient of turnover rate for pool X (d^{-1}), C_x is the concentration in the soil C in pool X (kg·m^{-3}·d^{-1}) and X is an organic matter pool.

In order to determine actual turnover rate coefficients (k_x), the standard turnover rate coefficients $(k_x^*)$are multiplied by two or three modifiers:

$$k_x = k_x^* F_m^T F_m^{\varphi} \left(F_m^{\tau}\right) \tag{2}$$

The turnover rates of SOM_1, SOM_2 as well as SMB1 are functions of the actual soil temperature $\left(F_m^T\right)$and the actual soil water potential $\left(F_m^{\varphi}\right)$and the soil clay content $\left(F_m^{\tau}\right)$. Turnover rates of SMB_2, AOM_1 and AOM_2 are only modified by F_m^T and F_m^{τ}.

DAISY model performed reasonably well in simulating trends in total soil carbon levels at most of the arable sites, but it could only simulate changes in the grassland site using assumptions on the plant-derived carbon inputs to the soil. The original calibration of the model parameters were based upon a limited input of organic matter (especially because rhizodeposition is ignored) and a constant decomposition rate (Sander *et al.* 2002) so the model has inability to simulate plant-derived carbon inputs during the growing period.

ITE Forest Model

ITE (Edinburgh) Forest (EF) and Hurley Pasture (HP) ecosystem models share a common soil sub-model.

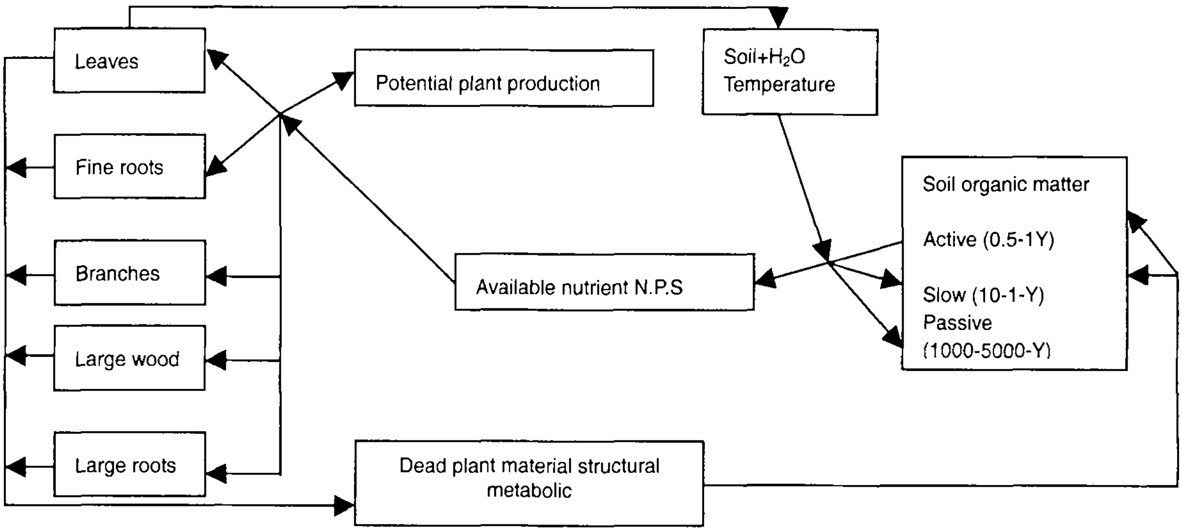

Fig. 2 Structure of the CENTURY ecosystem model

The relatively simple soil sub-model is shown in Fig. 3 and Fig. 4. The soil is treated as a single homogeneous layer with the SOM compartments. Carbon is cycled between biomass and (dead) SOM with a respiration loss on each transformation. The rates of all microbial mediated transformations depend on the size of the biomass and substrate pools, the temperature and the moisture potential. Soil moisture potential is determined from the moisture content by using a simple power-law which is approximate to the moisture characteristic curve. In Fig. 4, SOM exists in three discrete fractions, which were labeled for 'unprotected', 'protected' and 'stabilized'. All turnover rates depend on temperature and moisture potential. The forms of these modifier functions are as follows (Thornley *et al.* 1989; Arah 1996): the temperature modifier is a quadratic, which is zero at 0 and unity at 20; the moisture potential modifier is a sensitive exponential, which is equal to unity at saturation (0 KPa) and declines rapidly as moisture potential falls. The three compartments of SOM pools are alike those of the model Century.

SOMM

The soil organic matter model (SOMM) is a mathematical formulization of the "humus form" concept (Chertov *et al.* 1997), which has been used in forest science since the last century. The model comprises three compartments (undecomposed litter, partially humified litter, humus of mineral topsoil) and six processes of mineralization and humification as influenced by litter nitrogen and ash contents, soil C/N ratio, temperature and moisture. The model represents a system of linear differential equations with variable coefficients. It was based on a set of classical laboratory works on the rate of organic litter composition in controlled conditions in dependence of temperature, moisture and chemical composition of the material (Kostychev 1889; Waxman *et al.* 1951; Mikola 1954; Alexandrova 1970). The main specific features of the model mean that the biomass of soil organisms represents a negligible part of all decomposed matter and has a high rate of decomposition (Giliarov 1965; Chernova 1978; Crossley *et al.* 1991). The basic model takes into account: litter fall mineralization, humification and nutrient release. The SOMM has additionally kinetic parameters reflecting the activity of other groups of decomposers, such as Bacteria, Arthropoda and Oligochaeta. It has also been used for a wide range of qualitative simulations of humus profile formation in all natural zones.

The SOILM model

The SOILM model simulates on a daily basis and in one dimension carbon and nitrogen dynamics in soil and crop as function of climate. The model can be divided into two sub-models, a crop growth part and a soil part. The soil is divided into several layers in differing depth. Each organic pool is divided into a carbon and a nitrogen part, which are interactive. In the model, simulated interactions between soil organic pools are that micro-organism consumes daily

fractions of litter and humus carbon, and the part of the consumed carbon is lost by the microbial maintenance respiration. The other part of the carbon is directly turned into humus and the rest is built into microbial biomass. By making a lot of experiments, most parameters were available. A few parameters were estimated by calibration against measurements. Thought simulated soil moisture content in the soil layer of 0-30 cm was overestimated, the influence on the soil organic sub-model was very low.

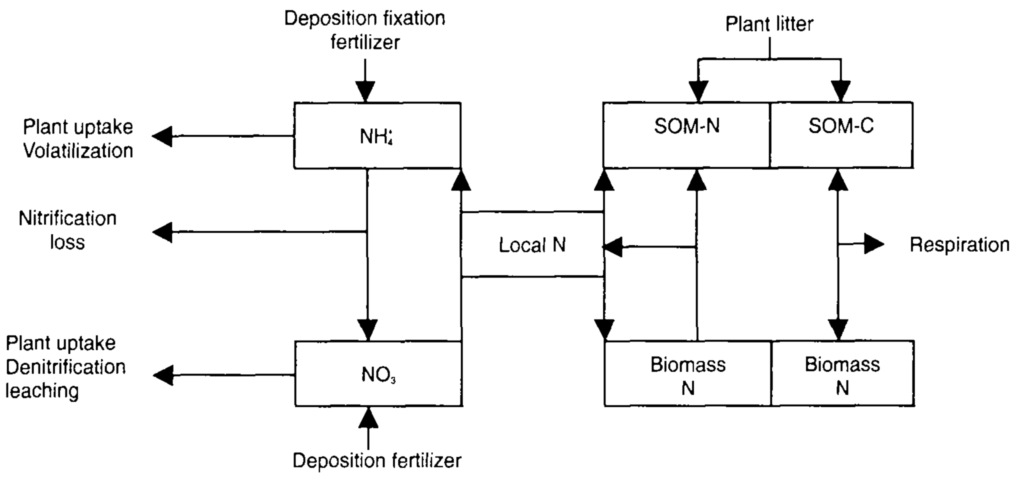

Fig. 3 Original SOM submodel common to the HP and EF ecosystem models

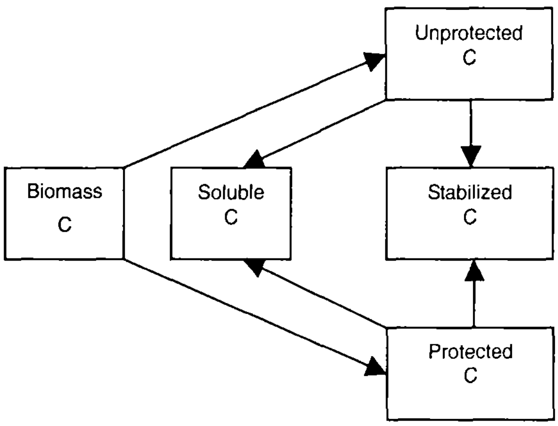

Fig. 4 New SOM submodel for HP ecosystem model

CANDY model

CANDY (Carbon and Nitrogen Dynamics) is a simulation system based on long-term experiments of organic matter turnover and nitrogen dynamics at Bad Lauchstadt, Germany. Main driving variables in the model are soil physical properties, meteorological data and management information. The main application of the CANDY model is the calculation of short-term dynamics of nitrogen transformation and long-term dynamics of organic matter turnover in arable soils. It contains the day-step model and the annual time-step model. The day-step model simulates dynamics of soil water and temperature and calculates a daily value of the turnover activity in terms of the biological active time (BAT). In the annual time-step model by the differential equations, a mean biologically active time and a constant annual flux of reproducing organic matter were assumptive. According to the goal, the daily or annual model was selected. The application of the daily model is limited in arable fields and requires a detailed soil description, daily meteorological data and land-use data during the whole period. The model was validated by a lot of datasets from very different sites. Its advantage is that the user has the ability to select different model specifications, depending on the available data and the problem to be solved. However one problem encountered in the model is that the estimation of the inert carbon is neglected in the turnover processes. The relationship between soil texture and the amount of inert carbon was not a constant for the different soil types. Consequently, it was necessary to use at least one observation of the carbon content of each site for the determination of the parameter (Franko *et al.* 1997).

Verberne model

In the model, the soil is treated as a multiplayer mineral soil system, and is simulated by using three sub-models: soil water submodel, soil organic matter submodel, and soil N submodel (Verberne *et al.* 1990). In organic matter submodel, the amounts decomposing from each pool are determined by an associated rate term, which is a matrix. This matrix briefly defines the flow of the carbon that decomposes from any one source pool to one or more product pools. Decomposition rates of soil carbon follow first-order kinetics. Specific decomposition rates are modified by soil moister and soil temperature, but microbial biomass does not affect decay rate. Clay content reduces microbial biomass turnover greatly. With highly clay content, protected organic matter content increases. The model emphasizes the influence of clay on soil organic components.

NCSOIL model

NCSOIL is a stand-alone model for homogeneous soil conditions and also the module of a larger model (NCSWAP) which simulates C and N transformations in the soil-water-air-plant system (Clay *et al.* 1985a; Clay *et al.* 1985b; Clay *et al.* 1989; Jabro *et al.* 1993; Jabro *et al.* Lengnick *et al.* 1993a; Lengnick *et al.* 1993b; Dou *et al.* 1995; Houot *et al.* 1996). The soil organic matter is divided into 4 pools: Pool I labile, Pool I resistant, Pool II and Pool III, with half-lives of 2, 17, 115 days and about 150 years, respectively. Pool I represents the microbial biomass (Nelson *et al.* 1979). Pool I and Pool II correspond to the potentially nineralizable N (Stanford *et al.* 1972; Molina *et al.* 1980; Molina *et al.* 1983); It is also referred to as the biologically active soil organic matter. The original version did not include stable organic matter (Molina *et al.* 1983). The sum of Pools I, II, and III – the soil organic matter, corresponds to that the total organic matter in soil minus residues. Each residue is described by 2 pools. Each pool decays follow first-order rate kinetics with respect to carbon concentration. Carbon decay rates are affected by water, temperature, clay content and N content. Due to too many initial variables when running the model, the model has been greatly simplified. With the development of the model, it has been incorporated into a deterministic model (NCSWAP), (Molina *et al.* 1984; Clay *et al.* 1985; Lengnick *et al.* 1994).

DNDC model

DNDC (DeNitrification and DeComposition), a process-based model, simulates carbon and nitrogen cycling in agro-ecosystems at a daily or subdaily time step. It consists of four interacting submodels: soil climate (including water flow and leaching), plant growth, decomposition, and denitrification. To simulate soil organic matter dynamics in agricultural land, DNDC requires as input: (1) climate data (daily air temperature and precipitation); (2) soil properties (bulk density, texture of clay content, PH, and the initial organic carbon content in the surface soil; (3) cropping practices. The model simulates turnover of organic matter in the soil, soil respiration, crop growth, and partitioning of crop biomass into roots, stems, and grain (Li 1994).

The current version of DNDC is able to simulate only agricultural ecosystems and contains a crop-growth module, but it doesn't take into account all factors that could influence crop biomass yield and weed growth during fallow periods. However it is not clear from any of these studies that inter-annual variability has a significant impact on long-term soil organic matter trends.

By linking Geographic Information Systems (GIS) that contain detailed information on soils, land use and climate to dynamics simulation models for the turnover of organic carbon, it is possible to estimate the impacts of land use and climatic changes on carbon stocks in soil. Recent studies have applied Rothamsted carbon model to natural forests and grasslands in New Zealand (Parshotam *et al.* 1995) and global studies (King *et al.* 1997), Century (Parton *et al.* 1988) to agro-ecosystems in the central United States (Donigan *et al.* 1994) and EPIN (Williams *et al.* 1985; Sharpley *et al.* 1990a, b) for tillage impacts on the US Corn Belt (Lee *et al.* 1993). This approach can attain a lot of spatial data and graphical display of outputs. Site specific input data for the model can also be provided at high resolution.

A GIS based integrated approach

GIS-linked modeling is a useful tool for large scale carbon cycle studies, allowing current estimates of regional carbon sequestration to be refined. It is also possible to analyze the sensitivity of particular combinations of perturbations in climate, land use and management. Hence, particularly sensitive systems and systems with great potential for carbon sequestration can be identified.

Lots of values and digitized map showing spatial distribution of annual decomposition rate of soil organic matter by GIS are needed in model. These preliminary calculations show how to couple a detailed GIS database with a dynamic simulation model, which can estimate regional SOC stocks and sequestration potential. The system should provide a flexible and powerful way to assess how different scenarios for land use, management and climatic change affect carbon dynamics at the regional scale. This approach shows the potential of GIS and RS in global scale.

From the studies and trends of models worldwide, we can observe that soil organic carbon models have been converting from regional to global scale. Developed models aggregate all processes producing in soil organic matter. Main influence factors such as climatic changes, land use and management have been considered in these models. With the development of technology, GIS and RS are useful tools for studying on large scale carbon cycle.

Conclusions

By comparison between soil organic models at home and abroad, soil organic matter model develops in following directions: Firstly, models are developed in the directions of the transition from empirical to mechanistic models. Empirical model is only based on the interrelation between soil organic matter variable and environmental factors, and cannot reflect nature system. Mechanistic models focus on dynamic change of soil forming process. These models can disclose the interactions of climatic change, land use and human activity, and predict dynamics of soil organic matter for decades; Secondly, based on the global carbon cycle, soil organic matter models must be coupling with climatic model and NPP model; Thirdly, some GIS-linked models for simulating temporal and spatial of carbon cycle should be developed at global scale.

Acknowledgments

The work was supported by National Natural Science Foundation (40231016) and Canadian International Development Agency (CIDA).

References

Adams, J.M., Faure, H., Faure-Denard, L, *et al.* 1990. Increase in terrestrial carbon storage from last glacial maximum to the present [J]. Nature, **378**: 711-714.

Arah, J.R.M. 1996. The soil submodel of the ITE Forest and Hurley Pasture ecosystem models [C]. In: Powlson, D.S., Smith, P., Smith, J.U. (Eds), Evaluation of Soil Organic Matter Models Using Existing Long-term Datasets. NATO ASI Series I, vol. 38. Springer, Heidelberg, pp. 225-230.

Bolin, B., Degens, E.T., Duvigneaud, P., *et al.* 1979. The global biogeochemical carbon cycle [C]. In: Bolin, B., Degens, E.T.,Kempe, S., Ketner, P.(Eds.), SCOPE 13. Wiley.Chichester, UK, pp.1-56.

Bolin, B., Degens, E.T., Duvigneaud, P., *et al.* 1979. The global biogeochemical carbon cycle [C]. In: Bolin, B., Degens, E.T., Kempe, S., Ketner, P. (Eds.), SCOPE 13. Wiley, Chichester, UK, pp. 1-56.

Bouwman, A.F.1990. Soils and the greenhouse effect [C]. In: Proceedings of the International Conference on soils and the Greenhouse Effect. Wiley, New York.

Changsheng, Li, *et al.* 1997. Simulating trends in soil organic carbon in long-term experiments using the DNDC model [J]. Geoderma, **81**: 45-60.

Chernova, N.M., Byzova, Ju.B. and Uvarov, A.V. 1975. Metabolicheskaya aktivnost I zhivoi ves razichnyh pantsymyh kleshchey lesnoi podstilki [C]. In: ed. N.M. Chernova, Rol Zhivothyh v Tunktsionirovanii Ekosistem. Moscow, pp. 151-154 (in Russian).

Chertov, O.G. and Komarov, A.S. 1997. SOMM-a model of soil organic matter dynamics [J]. Ecol Model, **94**: 177-189.

Chertov, O.G., Komarov, A.S., Crocker, G., *et al.* 1997. Simulating trends of soil organic carbon in seven long-term experiments using the SOMM model of the humus types [J]. Geoderma, **81**: 121-135.

Chertov, O.G., Komarov, A.S., Tsiplianovsky, A.V. 1999. Simulation of soil organic matter and nitrogen accumulation in Scots pine plantations of bare parent material using forest combined model EFIMOD [J]. Plant Soil, **213**: 31-41.

Clay, D.E., Clapp, C.E., Linden, D.R., *et al.* 1989. Nitrogen-tillage-residue management [J]. III. Observed and simulated interactions among soil depth, nitrogen, mineralization, and corn yield. Soil Sci., **147**: 319-325.

Clay, D.E., Clapp, C.E., Molina, J.A.E., *et al.* 1985b. Nitrogen-tillage-residue management. II. Calibration of potential rate of nitrification by model simulation [J]. Soil Sci. Soc. Am. J., **49**: 322-325.

Clay, D.E., Clapp, C.E., Molina, J.A.E., *et al.* 1985a. Nitrogen-tillage-residue management. I. Simulating soil and plant behavior by the model NCSWAP [J]. Plant Soil., **84**: 67-77.

Crossley, Jr., D.A., Coleman, D.S., Hendrix, P.F., *et al.* 1991. Modern Techniques in Soil Ecology [J]. Elsevier, Amsterdam, **60**: 164-167.

Donigan, A.S., Barnwell, T.O, Jackson, R.B, *et al.* 1994. Assessment of alternative management practices and policies affecting soil carbon in agroecosystems of the central United States [R]. EPA/600/R-94/067. Environmental Research Laboratory, Athens, Ga.

Dou. Z. and Fox, R.H. 1995. Using NCSWAP to simulate seasonal nitrogen dynamics in soil and corn [J]. Plant Soil, **177**: 235-247.

Eswaran, H., Vandenberg, E. and Reich, P. 1993. Organic carbon in soils of the world [J]. Soil Sci. Sco. Am. J., **57**: 192-194.

Franko, U. Crocker, G.J., Grace, P. R., *et al.* 1997. Simulating trends in soil organic carbon in long-term experiments using the CANDY model [J]. Geoderma, **81**: 109-120.

Houot, S., Cadot, L. and Molina, J.A.E., 1996. simulation by NCSWAP of the nitrogen dynamics under crops amended with sewage sludge in two soils [C]. In: Van Cleemput *et al.* (Eds.), Progress in Nitrogen Cycle Studies. Kluwer, Amsterdam, pp. 413-418.

Huang Yiao, Liu Shiliang, Shen Qirong, *et al.* 2001. Model establishment for simulating soil organic carbon dynamics [J]. Scientia Agricultura Sinica, **34** (5): 465-468.

Hudson, J.M., Gberini, S.A. and Goldstein, R.A. 1994. Modeling the global carbon cycle: nitrogen fertilization of the terrestrial biosphere and the "missing" CO_2 sink [J]. Global Biogeochem.Cycles, **8**: 307-333.

Jabro, J.D., Jemison, J.M.Jr., Lengnick, L.L, *et al.* 1995. Field validation and comparison of LEACHM and NCSWAP models for predicting nitrate leaching [C]. Proc. Int. Symp. On Water Quality Modeling, April 2-5, 1995, Orlando, Fla. American Society of Agricultural Engineering, pp. 137-147.

Jabro, J.D., Jemison, J.M.Jr., Lengnick, L.L., *et al.* 1993. Field validation and comparison of LEACHM and NCSWAP models for predicting nitrate leaching. [J]. Trans. ASAE., **36**: 1651-1657.

Jenkinson, D.S. 1990. The turnover of organic carbon and nitrogen in soil, phil [J]. Trans. R.Soc. Lond. B, **329**: 361-368.

Jenkinson, D.S. and Rayner, J.H. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments [J]. Soil Sci., **123**: 298-305.

Jenkinson, D.S., Adams, D.E. and Wild, A. 1991. Model estimates of CO2 emissions from soil in response to global warming [J]. Nature, **351**:304-306.

King, A.W., Post, W.M. and Wullschleger, S.D. 1997. The potential response of terrestrial carbon storage to changes in climate and atmospheric CO_2. Clim Change, **35**: 199-127.

Lai, R. 1999. Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect [J]. Prog. Environ. Sci., **1**(4): 307-326.

Lee, J.J, Phillips, D.L. and Liu, R. 1993. The effect of trends in tillage practices on erosion and carbon content of soils in the US Corn Belt. Water Air Soil Pollut., **70**: 389-401.

Lengnick, L.L. and Fox, R.H. 1993a. Simulation by NCSWAP of seasonal nitrogen dynamics in corn: I. Soil nitrate [J]. Agron. J., **86**: 167-175.

Lengnick, L.L. and Fox, R.H. 1993b. Simulation by NCSWAP of seasonal nitrogen dynamics in corn: II. Corn growth and yield [J]. Agron. J., **86**: 176-182.

Li Zhongpei and Wang Xiaoju. 1998. Simulation of soil organic carbon dynamic after changing landuse pattern in hilly red soil region [J]. Chinese Journal of Applied Ecology, **9**(4): 365-370. (In Chinese)

Li, C. Frolking, S. and Harriss, R.C. 1994. Modeling carbon biogeochemistry in agricultural soils [J]. Global Biogeochem Cycles. **8**:237-254.

McGuire, A.D., Melillo, J.M., Kicklighter, D.W., *et al.* 1995. Equilibrium responses of soil carbon to climate change: empirical and process based estimates [J]. J. Biogeogr., **22**: 785-796.

Metherell, A.K., Harding, L.A., Cole, C.V., *et al.* 1993. CENTURY soil organic matter model environment, technical documentation [C]. Agroecosystem Version 4.0. Great Plains.

Molina, J.A.E., Clapp, C.E. and Larson, W.E., 1980. Potentially mineralizable nitrogen in soil: A simple exponential model does not apply

for the first 12 weeks of incubation [J]. Soil Sci. Soc. Am. J., **44**: 442-443.

Molina, J.A.E., Clapp, C.E., Shaffer, M.J., *et al.* 1983. NCSOIL, a model of nitrogen and carbon transformations in soil: Description, calibration and behavior [J]. Soil Sci. Soc. Am. J., **47**: 85-91.

Nelson, D.W., Martin, J.P. and Erwin, J.O. 1979. Decomposition of microbial cells and components in soil and their stabilization through complexing with model humic acid-type phenolic polymers [J]. Soil Sci. Soc. Am. J., **43**: 84-88.

Parshotam, A., Tdte, K.R. and Giltrap, D.J. 1995. Potential effects of climate and land use change on soil carbon and CO_2 emissions from New Zealand's indigenous forests and unimproved grasslands [J]. Weather Clim., **15**(2): 3-12.

Parton, W.J., Schimel, D.S., Ojima, D.S., *et al.* 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management [C]. In: Bryant R.B., Arnold R.W. (eds.), Quantitative modeling of soil forming processes. SSSA Special Publication no.39. ASA, CSSA, SSA, Madison, Wis., pp 137-167.

Parton, W.J., Schimel, D.S., Cole, C.V., *et al.* 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands [J]. Soil Sci. Soc. Am. J., **51:** 1173-1179.

Parton, W.J., Scurlock, J.M.O., Ojima, D.S., *et al.* 1993. Observation and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem [J]. Cycles, **7:** 785-809.

Parton, W.J., Stewart, S.W.B. and Cole, C.V. 1988. Dynamics of carbon, nitrogen, phosphorus and sulfur in cultivated soils. A model [J]. Biogeochemistry, **5**: 109-131.

Parton, W.J., Stewart, S.W.B. and Cole, C.V. 1988. Dynamics of carbon, nitrogen, phosphorus and sulfur in cultivated soils. A model [J]. Biogeochemistry, **5:** 109-131.

Saha, S.K and Sing, B.M. 1991. Soil Erosion Assessment and Mapping of the Aglar River Waterheld (Uttar Pradesh) using Remote Sensing techniques [J]. Jour. Ind. Soc. Rem. Sens., **19** (2): 67-76.

Schimel, D.S., and Parton, W.J. 1986. Microclimatic controls of nitrogen mineralization and nitrification in shortgrass steppe soils [J]. Plant Soil, **93:** 347-357.

Schimel, D.S., Braswell, B.H., Holland, E.A., *et al.* 1994. Climate,edaphic and biotic controls over storage and turnover of carbon in soils [J]. Global Biogeochemical Cycle, **8**: 279-293.

Sharpley, A.N., Williams, J.R. (eds). 1990a. EPIC-erosion/productivity impact calculator. 1. Model documentation[R]. USDA Technical Bulletin No. 1768, Washington, DC.

Sharpley, A.N., Williams, J.R. (eds). 1990b. EPIC-erosion/productivity impact calculator. 2. User manual [R]. USDA Technical Bulletin No. 1768, Washington, DC.

Stanford, G., Smith, S.J. 1972. Nitrogen mineralization potentials of soils [J]. Soil Sci. Soc. Am. Proc., **36**: 465-472

Sundquist, E. 1993. The global carbon dioxide budget [J]. Science, **259**: 934-941.

Thornley, J.H.M. and Verberne, E.L.J. 1989. A model of nitrogen flows in grassland [J]. Plant Cell Environ, **12:** 863-886.

Van der Linden, M.M.A., Van Veen, J.A., Frissel, M.J. 1987. Modelling soil organic matter levels after long-term applications of crop residues, and farmyard and green manures [J]. Plant Soil, **101**: 21-28.

Van Keulen, H. and Seligman, N.G. 1987. Simulation of Water Use, Nitrogen Nutrition and Growth of a Spring Wheat Crop [J]. PUDOC, Wageningen, **99**: 310-312.

Van Veen, J.A. and Paul, E.A. 1981. Organic carbon dynamics in grassland soils, I. Background information and computer simulation [J]. Can. J. Soil Sci, **61:** 185-201.

Verberne, E.L.J., Hassink, J., De Willigen, P., *et al.* 1990. Modelling organic matter dynamics in different soils [J]. Neth, J. Agric, Sci., **38**: 221-238.

Williams J R. and Renard K G. 1985. Assessment of soil erosion and crop productivity with process models (EPIC) [C]. In: Follett R F, Stewart B A (eds). Soil erosion and crop productivity. ASA/CSSA/SSSA, Madison, Wis., 67-103.

Wu Jinshui, Liu Shoulong and Tong Chengli. 2003. Principles in modeling the turnover of soil organic matter using computer simulation [J]. Acta pedologica sinica, **40**(5): 768-774.